Initial Lab and Sky Test Results for the Teledyne Imaging System's H4RG-10 CMOS-Hybrid 4k Visible Array for Use in Ground- and Space-based Astronomical and SSA Applications

Bryan N. Dorland
U.S. Naval Observatory, 3450 Mass. Ave. NW, Washington, D.C. 20392
Ralph A. Gaume
U.S. Naval Observatory, 3450 Mass. Ave. NW, Washington, D.C. 20392
Gregory S. Hennessy
U.S. Naval Observatory, 3450 Mass. Ave. NW, Washington, D.C. 20392
Chris Rollins
Research Support Instruments, 4325-B Forbes Blvd., Lanham, MD 20706

ABSTRACT

We discuss the Joint Milli-Arcsecond Pathfinder Survey, the associated technology development, and the potential use of this technology to future space missions, including space situational awareness applications. We include a description of recent test results using CMOS-Hybrid technology and future plans for technology maturation.

1. INTRODUCTION

The Joint Milli-Arcsecond Pathfinder Survey (J-MAPS) is a proposed space astrometry mission. The purpose of the mission is to observe bright stars, including all 118,218 stars in the Hipparcos catalog [1] with high accuracy, generating a 2011-epoch astrometry catalog more or less complete through 12th magnitude with observations to 14—15th magnitude. The catalog will have an astrometric accuracy of 1 milliarcsecond (mas) /1 mas year^{-1}/1 mas (position, proper motion and parallax) through 12th magnitude, and be tied directly to the International Celestial Reference Frame (ICRF) [2] by observations of at least 100 extra-galactic sources down to 16th magnitude. The output catalog will include broad (CCD) band magnitudes as well as selected color information. The mission will support a number of national security space needs, including orientation, space situational awareness (SSA), and science and technology risk reduction.

In this paper we discuss recent technology development for the mission with a focus on potential SSA implications for both J-MAPS and other, future missions.

2. OVERVIEW OF THE J-MAPS MISSION

J-MAPS is a star-mapping mission. It is essentially a next-generation, very high accuracy star tracker proof-of-concept that is flown on a dedicated microsatellite bus (fig. 1). Minimum primary mission lifetime is 2 years, with a goal of 3 years. Post-primary mission operations are possible in support of additional star-mapping, SSA, or other applications. The baseline orbit is a 900-km Sun Synchronous Orbit (SSO) aligned approximately along the terminator, though other orbits are possible and under active study.

The J-MAPS concept of operations is as follows. The instrument will observe an area of approximately 1.2° x 1.2° for twenty seconds. The entire spacecraft will then spend ten seconds slewing half a field and settling, and repeat the imaging exposure. The instrument will oobserve “melon slices” of the sky, extending from celestial north to celestial south poles, with the observations generally contained along an annular region 90° ± 20° from the Sun—Earth axis. This orientation (i.e., “quadrature” from the Sun) will maximize the parallax signal, one of the critical observables for the mission. During a single “melon slice,” a given star will be observed four times; during a single “epoch” (3 day period), a single star will be observed 12 times. In general, there are two epochs per year, separated by six months.

Report Documentation Page			*Form Approved OMB No. 0704-0188*
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.			
1. REPORT DATE **2007**	2. REPORT TYPE		3. DATES COVERED **00-00-2007 to 00-00-2007**
4. TITLE AND SUBTITLE **Initial Lab And Sky Test Results For The Teledyne Imaging System's H4RG-10 CMOS-Hybrid 4k Visible Array For Use In Ground- And Space-based Astronomical And SSA Applications**			5a. CONTRACT NUMBER
			5b. GRANT NUMBER
			5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)			5d. PROJECT NUMBER
			5e. TASK NUMBER
			5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **U.S. Naval Observatory,3450 Mass. Ave.NW,Washington,DC,20392**			8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)			10. SPONSOR/MONITOR'S ACRONYM(S)
			11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**			
13. SUPPLEMENTARY NOTES **Proceedings of the Advanced Maui Optical and Space Surveillance Technologies Conference, held in Wailea, Maui, Hawaii, September 12-15, 2007**			
14. ABSTRACT **We discuss the Joint Milli-Arcsecond Pathfinder Survey, the associated technology development, and the potential use of this technology to future space missions, including space situational awareness applications. We include a description of recent test results using CMOS-Hybrid technology and future plans for technology maturation.**			
15. SUBJECT TERMS			

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**10**	

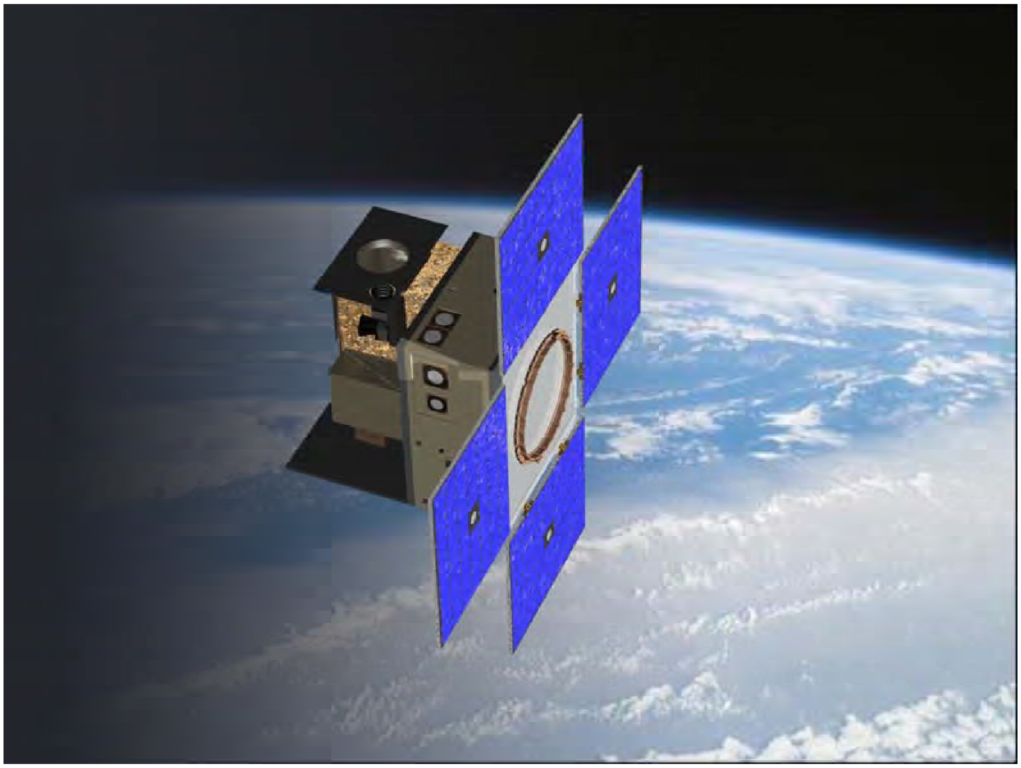


Figure 1. J-MAPS concept study design. The J-MAPS bus is approximately 2' x 2' x 2' in size, excluding the deployed solar cells. Total spacecraft mass is approximately 114 kg. Spacecraft shown in baseline 900-km SSO/terminator orbit.

The spacecraft is designed to spend up to 10% of the mission time outside of this observing region. During this time, arbitrary regions of the sky can be observed (to within ~70° of the Sun) or SSA observations can be made.

Full-frame imagery data will not be collected on-orbit. Rather, relatively small windows around each star will be saved as the science data are read out. The window data will be transmitted to the ground during regular downlinks and processed on the ground. Over the course of the two to three year mission life, the 40—75 observations of each star will be combined to generate a global astrometric and photometric catalog that is linked directly to the ICRF.

Other types of observations (full-frame images, dedicated target fields, SSA observations, calibration data, etc.) will be transmitted to the ground during downlinks and processed separately from the regular star mapping data.

3. THE J-MAPS INSTRUMENT

The baseline J-MAPS instrument is a 15-cm effective aperture, f/25 visible telescope (fig.2). The specifications for the optical elements are: as-built wave front error < $\lambda/15$ at 633 nm and peak distortion of < 10 mas across the 1.2° x 1.2° field of view (FOV). The current design calls for fabrication of the optical elements and optical telescope assembly (OTA) out of silicon carbide (SiC) in order to minimize temperature effects. A filter wheel mechanism will be incorporated into the instrument that will provide for wide-band Silicon response (i.e., 400-1000 nm) along with a to be decided (TBD) set of photometric filters. The mission may also include a grating filter to assess the utility of collecting dispersed spectra on-orbit.

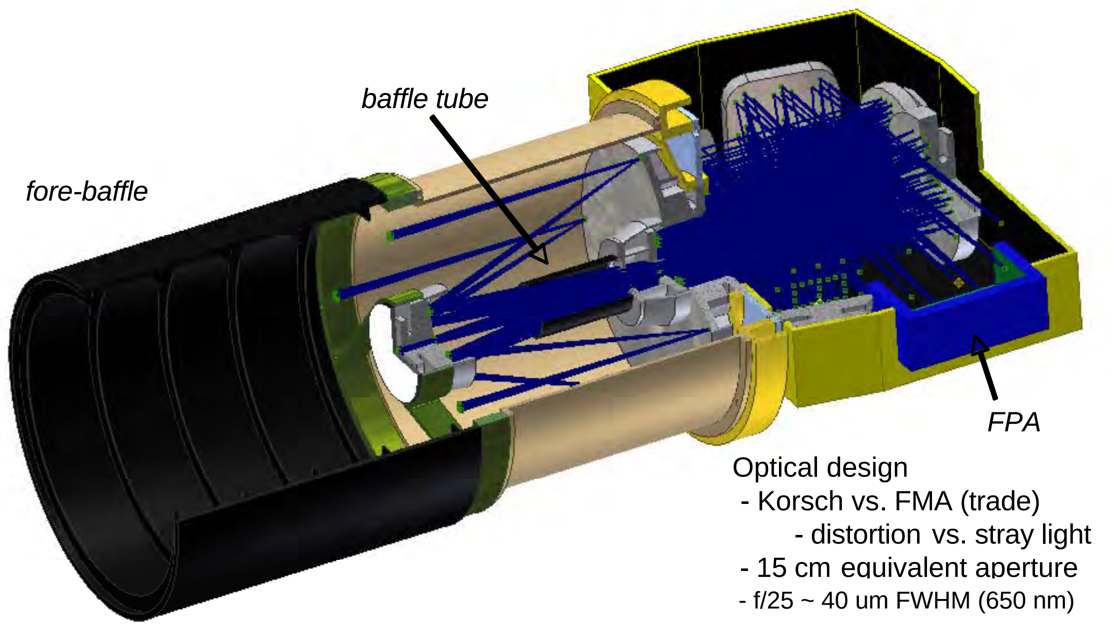


Figure 2. J-MAPS telescope design. The OTA is contained within a volume of approximately 2' x 8" x 10". Both the optical elements and OTA are fabricated out of SiC in order to minimize thermal gradients and CTE mismatch with the FPA.

The baseline design calls for a single 8k x 8k CMOS-Hybrid focal plane assembly (FPA)[1]. The leading candidate is currently the H8RG-10 variant of Teledyne Imaging System's HxRG-10 family of CMOS-Hybrid silicon chip assemblies (SCAs), though other solutions are being considered as alternatives. These include large, monolithic front-side CMOS, monolithic back-side CMOS, and other CMOS-Hybrid designs. The primary driver towards CMOS-related technology is the flexibility of the readout vs. CCDs, and CMOS have become increasingly competitive vis-à-vis CCDs with recent improvements in CMOS performance. We discuss the comparative advantages and disadvantages of CMOS, CMOS-Hybrid and CCDs in §4.

The J-MAPS camera electronics box (CEB) is a space-qualified, high-performance command and data handling system that operates the FPA and collects, digitizes, and stores data. The CEB uses an innovative design that will demonstrate the use of ASIC FPA control, and ASIC based navigation integrated with primary astrometric data collection. The CEB consists of four cards: Single Board Computer (SBC), ASIC card, Memory card, and Low Voltage Power Converter (LVPC) card. The SBC card is based on the Maxwell SCS750, and is a radiation-hard processor with processing power of up to 1800MIPS. The ASIC Card uses five Teledyne SIDECAR ASICs to interface to the 128-output FPA; one ASIC provides required timing signals, biases, and addressing, while the other 4 ASICs perform channel pre-amplification and 16-bit A/D conversion. The Memory Card collects streaming FPA data in temporary buffers and stores processed data prior to downlink with up to 64Gbits of error-corrected usable memory and a storage rate of 1Gbits/s. The LVPC card uses ~80% efficient hybrid DC/DC converter modules to provide power for the CEB box, with in-rush current protection and controlled start-up circuits.

The J-MAPS attitude determination and control system is a critical driver for use of a CMOS-type Readout Integrated Circuit (ROIC) rather than a CCD. Use of a CMOS-type ROIC enables simultaneous guidance and collection of science data using the same detector. CCDs would require, for example, the use of supplemental detectors arrayed around the primary detector. This would have significant disadvantages for

---

[1] Here, focal plane assembly (FPA) is used to indicate a single, integrated hybrid sensor consisting of detector, bonding and ROIC layers.

the mission. As it stands, with the CMOS-Hybrid, attitude determination is a two-step process. First, a pair of 30 arc-second star trackers are used to determine coarse attitude. Second, the coarse attitude is used to place boxes around the predicted positions of reference guide stars on the FPA. These window are read out at 5 Hz, the instrument quaternion is calculated, and is used to drive the attitude determination and controls system (ADCS). The ADCS guidance loop is thus closed using observations from the primary instrument.

Science data are downlinked to the ground along with supporting telemetry and housekeeping data. Star positions are determined from the window data and a global solution is determined using the technique of global block adjustment (BA) [3].

The instrument has been designed to simultaneously optimize the single measurement accuracy and the field of view. See [4] for a discussion of the specific trade-offs and accuracies associated with a single-aperture global astrometric observing program. It should be noted that the instrument is designed to use "optimal astrometric sampling," determined by both simulation and experience [5] to be approximately 2 pixels per full width half-maximum (FWHM), where optimal astrometric sampling is used to indicate the smallest single-measurement centroiding error. J-MAPS, in other words, is specifically designed to measure the position of stellar objects with maximum accuracy. This will be relevant in the discussion of SSA applications in §7.

4. CCDS VS CMOS AND CMOS-HYBRID

CCDs have historically been the standard solution for space-based visible detectors in both the defense and civilian sectors for decades. This is because CCDs have been the only detector solution that reliably delivers very low read noise, very low dark current, and very high quantum efficiency.

CCDs, however, have limitations. They are susceptible to the ambient charged particle radiation present in the orbital environment, displaying both dark current degradation and bulk (i.e., displacement) damage over time. Because they are inherently serial readout devices, they have flexibility limitations. While there do exist more flexible readout options with CCDs (e.g., frame transfer, interline transfer, orthogonal transfer, etc.), these solutions tend to come at a cost of added complexity and tradeoffs such as lost photosensitive area.

CMOS detectors are, in many respects, complementary to CCDs. CMOS ROICs are extremely flexible, capable of supporting read-while-integrate, random access windowing, and random access pixel reset. CMOS ROICs are, are typically lower power and generate less heat than CCDs, can support camera-on-a-chip fully digital output from the FPA and full electronic shuttering including both rolling and snapshot read. CMOS are also inherently less sensitive to some manifestations of radiation damage than CCDs. Unlike CCDs, which transport charge to the amplifier by shifting it through the silicon substrate, CMOS pixels are read out directly on a pixel-by-pixel basis. Thus, while high energy particle damage still causes the generation of traps in the Si substrate, the conduction-band electrons are not exposed to hundreds or thousands of pixels worth of traps during readout. As a result, charge transfer inefficiency (CTI) considerations are not a significant issue, even at end-of-life (EOL). We note that another major effect of radiation exposure—secular increase in dark current—is similar for both CCDs and visible CMOS.

The drawback with CMOS detectors historically has been performance. CMOS has had higher read noise, increased dark current, reduced fill factor (and thus, reduced absolute quantum efficiency) and the implanted readout circuitry on the photosensitive area of the detector introduces intra-pixel and focal ratio sensitivity dependencies.

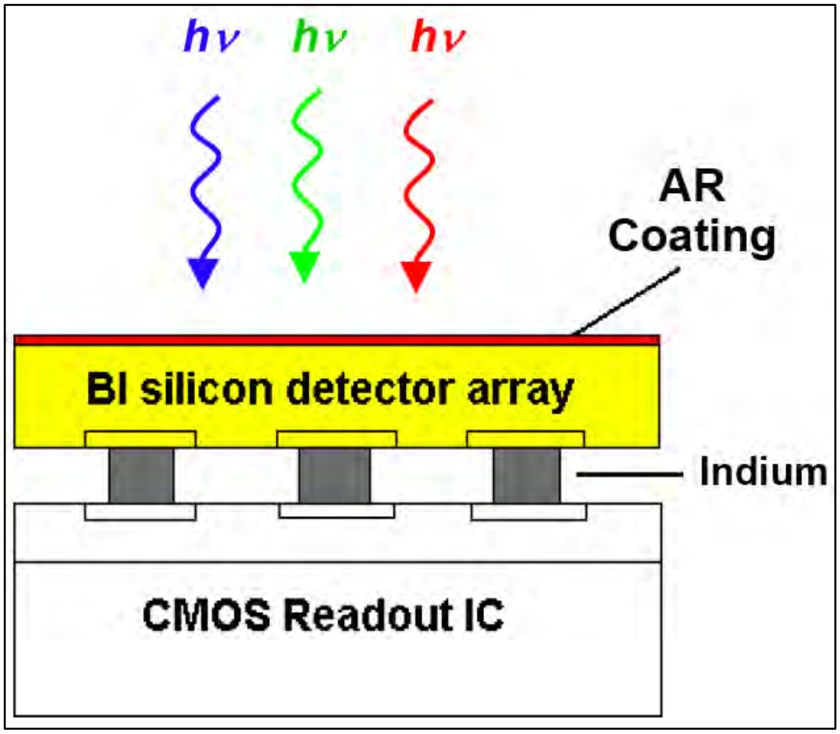


Figure 3. CMOS-Hybrid cross sectional diagram showing detector, readout and connecting indium bump-bonds. Diagram from TIS; used with permission.

Recent advances in both hybridization and back-side illuminated CMOS seek to address these deficiencies. Our current assessment is that the CMOS-Hybrid approach is more mature than back-side CMOS. Fig. 3 is a cross-sectional diagram of a typical CMOS-Hybrid design. Hybridization involves mating a CCD-like detector layer with a CMOS ROIC; in this case, hybridization is effected by means of indium bump-bonds. This type of design separates the charge-generation function (the detector) from the readout function (the ROIC), allowing for optimization of both. For visible sensors, the detector is typically made of silicon. For infrared (IR) applications, the detector can be fabricated out of material such as mercury-cadmium-telluride (HgCdTe) that is sensitive to IR radiation while using the same ROIC. Use of this dedicated detector layer eliminates the fill factor and implanted circuitry problems associated with monolithic CMOS. Continued development and maturation of the detector and ROIC technology for a variety of missions and needs has resulted in reduced read noise and overall better performance that is beginning to approach CCDs for high-performance science applications. See [6] for a detailed discussion of CMOS, CMOS-Hybrid and CCDs relative strengths and weaknesses.

5. DESCRIPTION OF THE H4RG-10 FPA AND GROUND TEST CAMERA

During the J-MAPS concept study and subsequent risk reduction activities, the Teledyne Imaging Systems (TIS) HxRG-10 class of astronomical CMOS-Hybrid detector was identified as the baseline detector solution. The HxRG-10 is a large format (scaleable from 4k to 16k) 10-micron pixel design intended for use in astronomy. As such, it is also designed to have low read noise and low dark current and high absolute QE.

USNO procured a first-spin H4RG-10 FPA as a prototype for the H8RG-10. The H4RG-10 is a smaller version of the H8RG-10, with a format size of 4k x 4k. The primary goal of the procurement was to establish the viability of the design, establish its performance baseline and provide feedback to the vendor for future improvements.

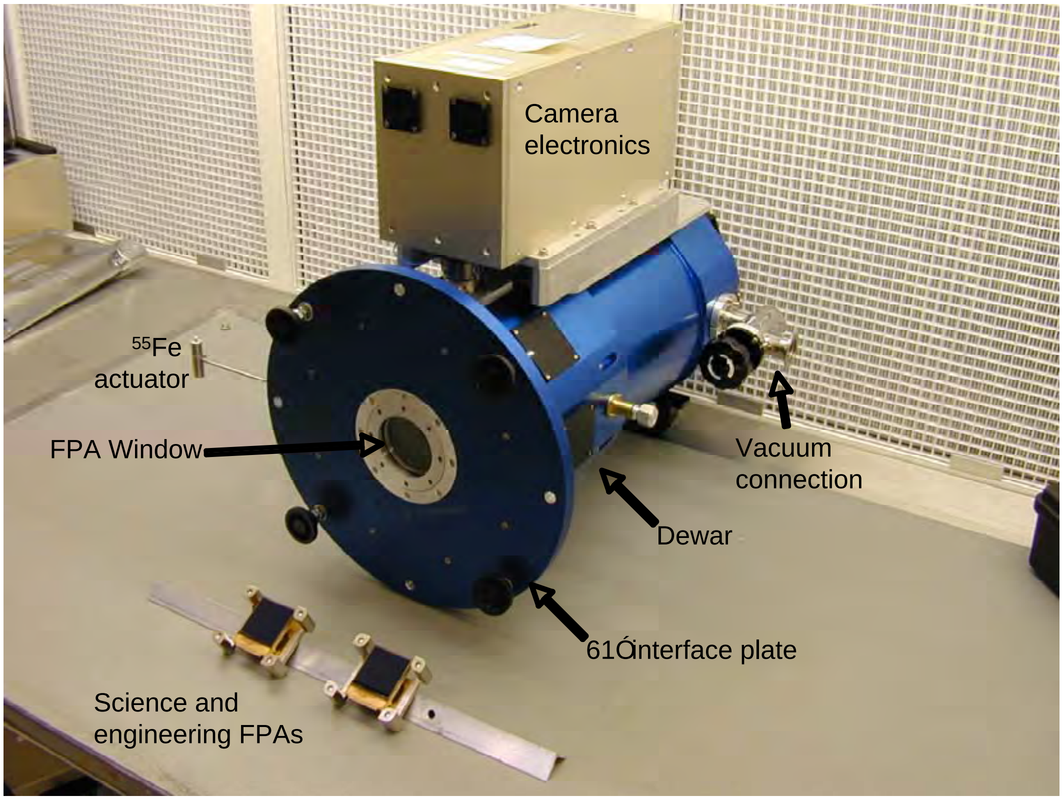


Figure 4. J-MAPS Ground Test Camera (GTC) and H4RG-10 prototype FPAs. The GTC was initially designed to be deployed at the USNO 61-inch Strand astrometric telescope in Flagstaff, AZ.

USNO received a fully-functioning ROIC in 2006, one engineering and one science grade complete FPAs in early 2007. A ground test camera (GTC) was built to test the FPA performance and to operate the detectors in the field. The camera is shown in Fig. 4 along with the two FPAs.

The GTC consists of a 16-bit, 32-channel Leach camera readout and control electronics unit, a Universal Cryogenics dewar with 24-hour hold time, a Lakeshore temperature control unit, and a controller/data acquisition system. The GTC reads out the FPA using 32 ports operating at up to 400 kpix/channel/sec. As a result, the entire FPA can be read out in approximately one second. Because the system supports random access windowing, selected regions of the FPA can be read out at much higher frame rates without impacting performance. Estimated camera electronics noise at these speeds is < 2 e- RMS.

The GTC was designed to be used with USNO's 61-inch Strand astrometric telescope located at NOFS. The design includes an Fe^{55} source on a sliding actuator, allowing the FPA to be directly irradiated for purposes of gain calculation, cross-talk measurement etc. The camera can be operated at FPA temperatures between 110 and 300 K, with a stability of 1 mK.

6. TEST RESULTS

Initial testing for the H4RG-10 FPAs was divided into two phases. The first phase was operating parameter optimization and characterization in the lab, and the second phase was field testing on USNO's 61-inch Strand astrometric telescope located at the USNO's Flagstaff Station in Flagstaff, AZ.

See [7] for a detailed discussion of the test results. For purposes of this paper, the most important findings are summarized below:

- Pixel operability: 99.8% at 50% signal level or higher

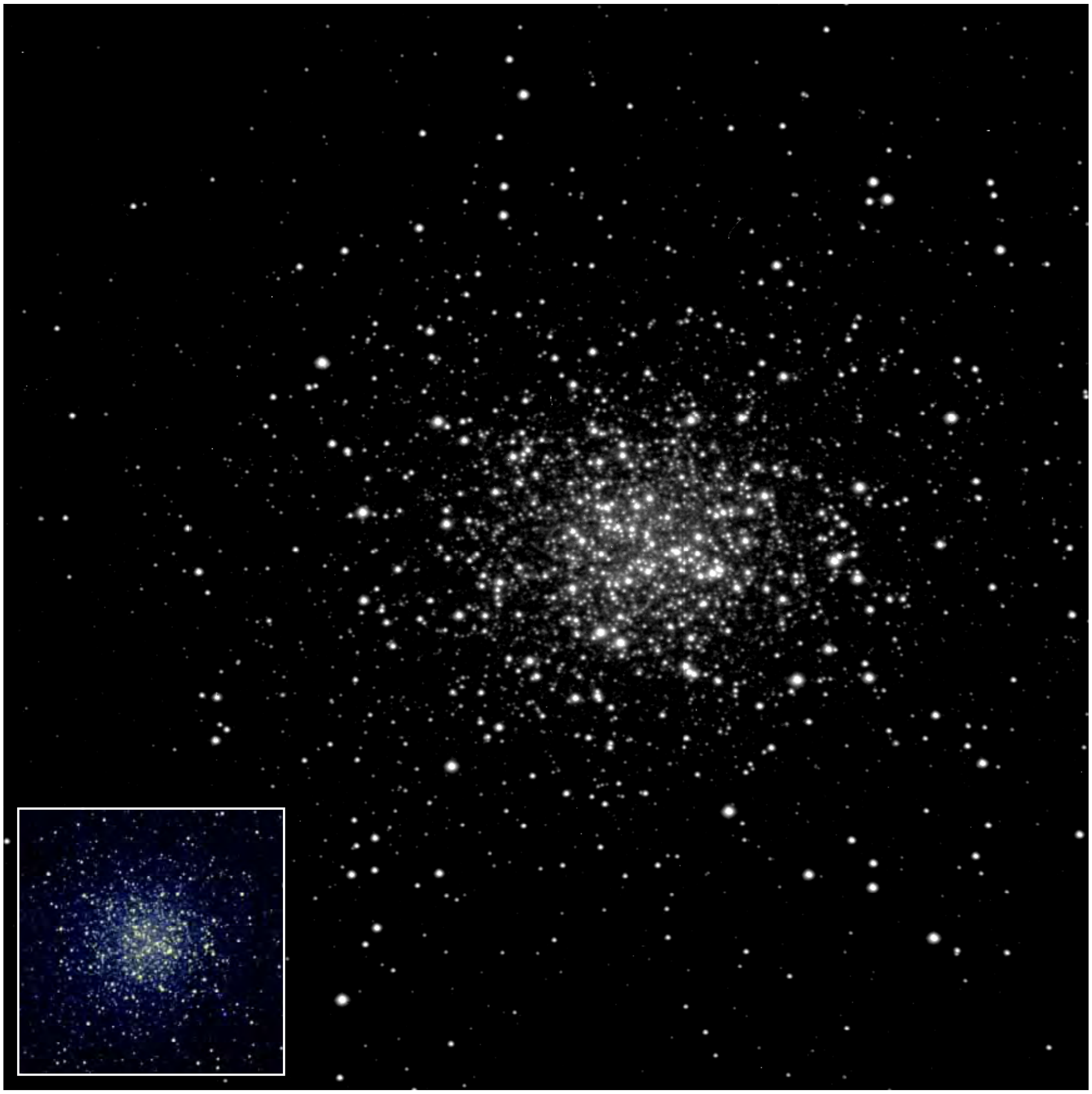


Figure 5. The globular cluster M13 as observed by the TIS H4RG-10 FPA deployed on US Naval Observatory's 61-inch Strand astrometric telescope in Flagstaff, AZ. Main image is 9.2' x 9.2' and is taken in I-band (near IR). (Inset) The central 5.2' x 5.2' (2300 x 2300 pixel) region in color. RGB colors are scaled from V, USNO astrometric A2 and I filters.

- Read noise (post-CDS[2]): 7 e- RMS
- Peak absolute QE: 93% (QE*fill factor)
- Dark current: 30—40 e- per pixel per second at 193 K
- Pixel cross-talk: 7% (adjacent/central pixel signal)
- Point source centroiding: < 1/40th pixel

The operability, read noise, and quantum efficiency results are very promising. The pixel cross-talk is believed to be due primarily to inter-pixel capacitance rather than optical cross-talk; its effect on science data is currently being evaluated and mitigation for future spins is also being evaluated.

[2] i.e., Correlated Double Sampling

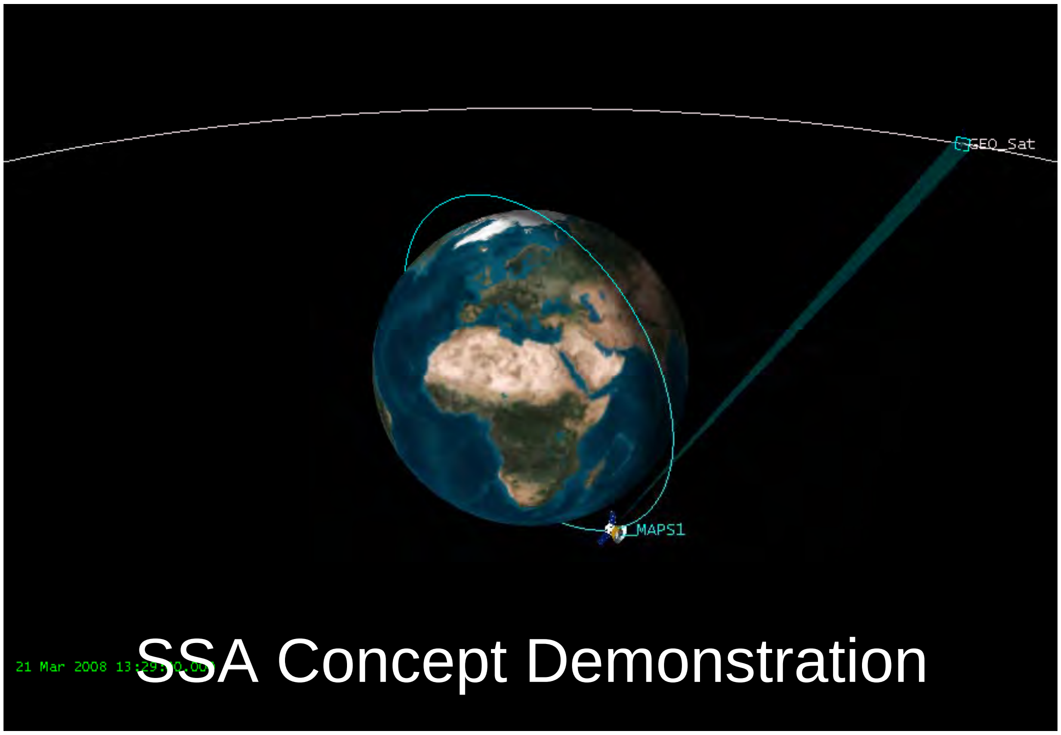


Figure 6. Visualization of J-MAPS SSA observation of GEO RSO target.

The most significant problem for the first spin devices is the high level of dark current. The mode dark level is approximately 30—40x higher than the goal, and the distribution of dark is skewed towards hot pixels. As a result, there is significant "salt and pepper" noise in the unprocessed data.

Fortunately the dark pixels are stable in time. As a result, reference dark images can be subtracted from science images to remove most of the dark. Unfortunately, this does not reduce the noise associated with the higher dark areas. Dark current in hot pixels also reduced the effective well capacity of the pixel, and in some cases (very hot pixels and long exposure times) the dark current can saturate the pixel.

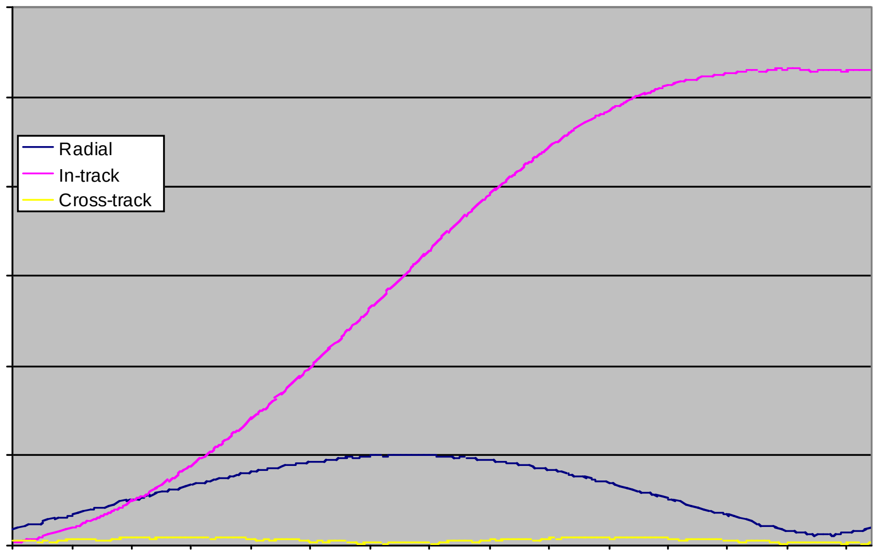
As a result, much of the effects of excessively high dark can be removed but not all. Fig. 5 is an image of the globular cluster M13 taken from the Strand telescope after CDS processing and dark subtraction. A joint effort by USNO, NASA, the Department of Energy (DOE) and members of the Large Synoptic Survey Telescope (LSST) project are working with TIS to identify and correct the problem or problems resulting in the excessive dark current for possible future spins of the FPA.

7. APPLICATIONS TO SSA OBSERVATIONS

As part of the testing, the flexible readout and rest capabilities of the FPA were all functionally verified. Assuming the basic CMOS-type technology can continue to be matured such that the performance approaches CCD-level, this type of detector is potentially highly promising for SSA use due to the readout flexibility. One of the mission goals of J-MAPS is to demonstrate these capabilities in orbit (fig. 6).

CCD-based SSA sensors typically take a single snapshot of an area of the sky and then process this image on-orbit or on the ground, extracting tracks and using the result information to generate, e.g., high-accuracy orbits. Orbital sensors require use of additional sensors (e.g., additional detectors on the focal plane or other sensors such as star trackers) in order to determine their orientation and to maintain attitude control. Use of these other sensors introduce error into the attitude determination process.

J-MAPS, on the other hand, will use a single instrument to simultaneously observe resident space object (RSO) targets and determine attitude. This is enabled by the CMOS-Hybrid FPA. Operating in either



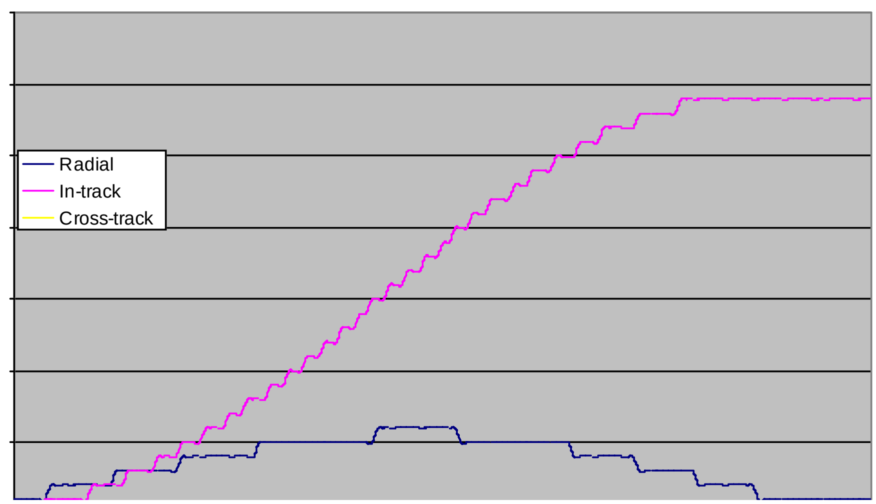


Figure 7. Rapid orbit determination simulations for J-MAPS. (Upper) CCD-like, full-frame images, three 20-sec observing epochs over two J-MAPS orbits. (Lower) High-frame rate, windowing mode accuracy limit, three FPA transits per orbit, two J-MAPS orbits.

sidereal track mode or GEO rate track mode, reference star positions will be read out at 5 Hz and used to guide the spacecraft attitude without interrupting the collection of RSO data. The RSO positions will be determined using the reference star positions. Use of a GEO rate track will allow longer integration times, supporting observations of RSOs down to 15^{th} or 16^{th} magnitude.

In addition, use of random access windowing supported by the H4RG-10 allows for much higher frame rates and much lower data rates coming off the instrument vs. a comparably sized CCD. Only pixels around objects of interest (stars, RSOs) need to be read out. Other pixels can be ignored and need not be processed or even read out. This allows "freezing" the RSO in place (or, alternately, the reference stars if tracking at the GEO rate) using very short integration times without suffering significant performance degradation. In this way, a GEO RSO could be tracked across the FPA over the course of a single transit, resulting in thousands of observations that can be combined into an orbit solution.

Simulations performed in support of the J-MAPS mission (see fig. 7) show that for best-case scenario where each one of these observations is uncorrelated with others taken during the same transit, orbital solutions with metric accuracies of the same order as the RSOs themselves are possible using a relatively limited number of epochs of data over a relatively short time period (one to two J-MAPS orbits, or < 200 minutes). This level of accuracy is enabled by the extreme precision of the measurements themselves, the high readout flexibility of the FPA and the high accuracy of the J-MAPS background reference star catalog.

If this class of SSA sensor can be demonstrated on orbit, it could have significant impact for a variety of different SSA needs. It can significantly improve the accuracy of the orbital elements for specific targets (catalog maintenance), it can be used to make very high accuracy conjunction assessment predictions, assisting operators in determining when and if blue satellites need to be maneuvered to avoid possible collisions, and it can be used for maneuver recovery and determination of intent on the part of a maneuvering spacecraft. J-MAPS, or derived sensor technology, would be used as a tasked or cued asset, used for high metric accuracy measurements for a small number of high interest targets in conjunction with other current and planned SSA assets.

8. FUTURE PLANS

Near-term: The J-MAPS ground test camera is being reconfigured for redeployment to NOFS for additional sky testing in the late CY07 timeframe. The testing will include RSO observations using both full-frame and rapid windowing mode using the USNO 1.3 m telescope. The testing will also include a full exercise of all the various advanced ROIC readout and reset capabilities.

Mid-term: USNO will continue to work with other interested parties and TIS to improve the performance of the HxRG-10 family of detectors and test future iterations. In addition, USNO will actively pursue CMOS-type solutions from other vendors, in conjunction with various government partners.

9. SUMMARY

USNO is pursuing development of large-format, high-performance CMOS-type FPAs for use in space astrometry and astronomy, specifically in support of the J-MAPS mission. The TIS HxRG-10 class of CMOS-Hybrid detector has been identified as the most promising given the J-MAPS FPA requirements. USNO recently procured and completed initial tests of an H4RG-10 FPA. The result of the testing is that certain aspects—most notably hybridization operability and read noise—look very promising, while other aspects—viz., dark current and hot pixel population—are highly problematic. Continued development of this particular detector technology may yield FPAs in the near to mid term future that can supplant CCDs in terms of overall SSA capabilities.

10. REFERENCES

1. Perryman, M.A.C., et al. 1997, Astronomy and Astrophysics, 323, L49

2. Charlot, P., Fey, A.L., Jacobs, C.S., Ma, C., Sovers, O.J., & Baudry, A. 2005, Journees 2004 - systemes de reference spatio-temporels, 21

3. Zacharias, N.1992, Astronomy and Astrophysics, 264, 296

4. Zacharias, N., & Dorland, B. 2006, Publications of the Astronomy Society of the Pacific, 118, 1419

5. Zacharias, N. 2004, Astronomische Nachrichten, 325, 631

6. Janesick, J.R. 2004, Proc. SPIE, 5167, 1

7. Dorland, B.N. et al., 2007, Proc. SPIE, 6690, 13